Comparison of predicted and derived measures of volatile organic compounds inside four new relocatable classrooms

A. T. HODGSON[1], D. G. SHENDELL, W. J. FISK, AND M. G. APTE

Indoor Environment Department, Environmental Energy Technologies Division, E.O. Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Mailing Address:

Mail Stop 70R0108B

Lawrence Berkeley National Laboratory

1 Cyclotron Road

Berkeley, CA 94720, USA

[1]Corresponding author. Tel.: +1-510-486-5301. Fax: +1-510-486-7303. E-mail: athodgson@lbl.gov

Abstract **-** Our objective was to develop a process for selecting interior finish materials having low impacts with respect to emissions of toxic and odorous volatile organic compounds (VOCs) for school relocatable classrooms (RCs). A laboratory study identified alternate materials with low VOC emissions. Two pairs of RCs subsequently were constructed. One RC per pair was constructed with standard interior materials; the other incorporated alternate materials. The pairs were sited side-by-side at two California elementary schools in fall 2001. VOCs were measured during school hours over eight or nine weeks in both fall cooling and winter heating seasons.

Indoor minus outdoor concentrations of 15 VOCs in the fall with an advanced HVAC operated were low; only formaldehyde concentrations exceeded 5 ppb. Classroom VOC emission rates (mg hr^{-1}) were predicted based on emission factors (μg m^{-2} hr^{-1}), material quantities and design ventilation rates. These were compared to values derived from measurements of VOC concentrations and ventilation rates at pre-occupancy, eight and 27 weeks. For six VOCs, derived emission rates at either pre-occupancy or eight weeks agreed within a factor of two of predicted rates in two or more RCs. Occupied school-hour concentrations of six of ten VOCs were significantly lower in modified RCs though differences were mostly less than 1 ppb.

Key words: Volatile organic compound; Formaldehyde; School classroom; Interior finish material; Emission rate

Practical Implications - Laboratory-based material testing combined with modeling and field validation to select low VOC-impact interior finish materials helped achieve the aim of providing generally acceptable air quality in new school relocatable classrooms (RCs). The accuracy of the combined process was evidenced by the correct prediction of air quality impacts, though small, due to material VOC emissions when the study RCs were ventilated at code-minimum requirements. The process could be generalized to other manufacturers and classroom types. Material selection also is important to accommodate reduced ventilation rate conditions, which likely occur in many classrooms.

Introduction

In California and elsewhere in the U.S., schools have become a focus of complaints regarding children's potential exposures to biological and toxic, airborne, chemical contaminants including formaldehyde and other volatile organic compounds (VOCs). Odorous VOCs also are of potential concern because they can adversely affect people's acceptance of indoor environments and possibly their performance. A few studies have been conducted to identify and quantify the material sources of toxic and odorous VOCs in new site-built and manufactured houses (Hodgson *et al*., 2000 and 2002, Lindstrom *et al*., 1995). Much less is known about the sources, composition, and concentrations of VOCs of concern in schools (Shendell *et al*., 2003), particularly in new relocatable classrooms (RCs, also termed modular or portable classrooms).

California is rapidly constructing new schools and additional classrooms. The State's public schools for grades K-12 currently enroll approximately six million students, with more than 200,000 staff. The projected rapid population growth of school aged children and class size reduction policies required increased classroom space. RCs provided school districts with a quick, convenient and relatively low cost way to add or replace classrooms.

Ensuring new RCs are both energy efficient and provide healthy environments for students and staff is an important goal for the State. The research task reported here was part of a larger project designed to address these twin issues. Specifically, the overall project goals were to engineer and evaluate an improved RC design incorporating an energy efficient heating, ventilating, and air conditioning (HVAC) system, with the potential to consume less energy and provide improved indoor air and environmental quality (IEQ) as compared to currently available RC models.

The task objective was to develop and demonstrate a process for selecting interior finish materials for RCs that have relatively low impacts with respect to their emissions of toxic and odorous VOCs, including formaldehyde and acetaldehyde. The task involved the participation of a large northern California manufacturer of conventional RCs and two northern California school districts. It was conducted as a two-stage study with both laboratory- and field-based components. The laboratory study objectives were to characterize the emissions of VOCs both from standard materials used to finish the interiors of this manufacturer's RCs and from alternate, non cost-prohibitive, easy to clean and maintain materials with potentially lower impacts on VOC concentrations in new classrooms (Hodgson *et al*., 2001). The results of the laboratory study were used to develop specifications for four new RCs. Two were designed with standard interior finishes, and two were designed to incorporate several alternate materials. In selecting the alternate materials, emphasis was placed on reducing concentrations of VOCs on governmental agency lists of toxic compounds (Table 1).

The classrooms were constructed in summer 2001 and installed in pairs at elementary schools in the two participating school districts for use starting with the fall semester. The classrooms were to be occupied by third and fourth grade children who spend most of their time in their homeroom. The classrooms were each uniquely equipped with two independent HVAC systems, a conventional compressor-based unit and an advanced system that was the subject of the energy efficient ventilation project task. The classrooms were instrumented to measure a number of energy use and IEQ parameters (Shendell *et al*., 2002). The impacts of the two HVAC systems were investigated over the fall and spring semesters using a case crossover design; each RC served as its own control, as the different HVAC systems were operated on alternate weeks. The study included the weekly measurement of school day integrated indoor and outdoor VOC concentrations and experiments to derive whole-building VOC emission rates. The measurements were used to determine: 1) if indoor air concentrations of VOCs of concern were reduced through the process we devised for interior material selection, and 2) if indoor VOC concentrations in the new classrooms were predicted with reasonable accuracy from the results of the laboratory study of material VOC emissions.

Methods

Laboratory Study Methods

The RC manufacturer provided samples of most standard classroom interior finish materials. These either were taken from stock or collected from the production facility. Samples of several standard materials were purchased. Material manufacturers provided samples of the alternate materials, which were specified to be newly produced. Samples were wrapped in multiple layers of aluminum foil. There were 17 material samples in total encompassing floor coverings, tackable wall panels and acoustical ceiling panels. Small-scale test specimens, with typical, exposed, surface area dimensions of 15 by 15 cm (0.02-m^2 area) were prepared for each material sample.

The emissions of VOCs from the test specimens were individually determined following the guidance of ASTM D 5116-97 (ASTM, 1997a). Specimens initially were conditioned at typical indoor conditions for ten days prior to emission testing. At the end of the conditioning period, a specimen was transferred to a 10.5-L stainless steel chamber. The chamber was maintained at 23 ± 1^{o} C temperature with a 0.059 ± 0.003 m^3 h^{-1} inlet flow rate of high purity nitrogen preconditioned to 50±5% relative humidity. Samples for the analysis of VOCs and aldehydes were collected from the chamber exhaust at 96-h elapsed time. Sampling media and analytical methods were identical to those given below for the classroom study.

The chamber samples were qualitatively analyzed to identify VOCs emitted by each material. Then, the samples were quantitatively analyzed for chemicals with odor thresholds below 1 ppm (Devos *et al*., 1990) and chemicals of concern listed by any of the three California programs regulating and/or assessing health risks of toxic chemicals [Table 1 (Cal/EPA, 1999, 2003a and 2003b)].

Material VOC emission rates, emission factors, and predicted classroom concentrations were calculated from the chamber results by mass balance. Details regarding the laboratory methods are presented elsewhere (Hodgson *et al*., 2001).

Classroom Study Methods

The field study was conducted at two elementary schools in two separate northern California school districts, designated School Districts (SDs) A and B. Working with the RC manufacturer and the school districts, we developed specifications for four new RCs, which were produced in late summer 2001 and installed at the schools for occupancy by the fall 2001 semester. The two source-modified classrooms were finished with alternate tackable wall panels, ceiling panels, and carpet (one school) as described under Results. Each classroom was equipped with two separate ventilation systems: a standard 10 SEER Heat Pump Air Conditioner (HPAC) system and an advanced indirect/direct evaporative cooling (IDEC) with hydronic heating system. A standard and a modified classroom were sited adjacent to each other at each of the two schools. These have been designated SDA-A, source modified classroom at SD A (formerly designated RC 2 in Hodgson *et al.*, 2001, 2002); SDA-B, standard classroom at SD A (formerly RC 1c); SDB-A, modified classroom at SD B (formerly RC 4); and SDB-B, standard classroom at SD B (formerly RC 3c).

Throughout the field study, each classroom was alternated on a weekly basis between the HPAC and IDEC systems. The changeovers were coordinated, *i.e.*, the two classrooms at each school were always operating on the same system. The classroom teachers had control of the fan and temperature settings. The study was conducted from August 2001 through March 2002 during eight and nine weeks in the fall cooling and winter heating seasons, respectively.

School-day integrated air samples (~7-8 hours) were collected for VOCs and aldehydes inside each classroom and outdoors at each school during mid-week. Active sampling systems, located within outdoor enclosures, consisted of timer-controlled peristaltic pumps (L/S® Fixed-Speed Drive, Cole-Parmer Instr. Co.) collecting single or duplicate samples. VOC gas samples were collected onto Tenax-TA™ sorbent tubes (CP-16251; Varian Inc.) modified by substituting a 15-mm section of Carbosieve S-III 60/80 mesh (10184, Supelco Inc.) at the outlet end. Aldehyde samples were collected on treated, 2,4-dinitrophenylhydrazine, silica-gel cartridges (WAT047205, Waters Corp.). The sampling media were located inside each classroom ~2.25 m above the floor and 0.7 m away from the back wall, and outside facing away from the standard HVAC system air inlet ~1 m from the back wall. Flow rates of the sampling systems, ~5-6 cm^3 min^{-1} for VOCs and ~150 cm^3 min^{-1} for aldehydes, were measured in the morning within 30 minutes after the start and in the afternoon. Duplicate indoor air samples, at least 10% overall for each sample type, were collected. Field blanks, 10% overall for each sample type, also were collected. Field method details are presented elsewhere (Shendell *et al.*, 2002).

Air samples were analyzed within two weeks of collection. VOC samples were analyzed by thermal desorption-gas chromatography/mass spectrometry generally following U.S. EPA Method TO-1 (U.S. EPA, 1984). Aldehyde samples were extracted and analyzed by high performance liquid chromatography with UV detection following ASTM standard method D-5197-97 (ASTM, 1997b). Standard deviations (i.e., precision) for the analyses were calculated by analysis of variance from the sample-pair data. The lower limit of quantitation (LOQ) for each compound was calculated as the 95% confidence interval of the precision. For compounds with measured outdoor concentrations, the LOQs for indoor minus outdoor concentrations were determined by propagation of uncertainties. Values below the LOQ were assigned one-half the LOQ in the data files for statistical analyses. The criteria for selecting target VOCs were the same as those used in the laboratory study.

Separate studies of VOC and aldehyde emission rates in unoccupied classrooms were conducted prior to occupancy and eight and 27 weeks after first occupancy. For the pre-occupancy sampling event, the classrooms were operated with the HPAC systems, which were positioned so the fans were on continuously. The systems had not been adjusted to their final settings at this time. For the subsequent two sampling events, the classrooms were operated with the advanced IDEC systems, which were on continuously. The IDEC systems were run over night. Ventilation rates were measured in the early evening and VOC samples were collected on the following morning prior to class.

Ventilation rates were determined by tracer gas decay. Pure carbon dioxide (CO_2) from a cylinder was injected in front of an air inlet to mix the gas in a classroom in the early evening. The initial target CO_2 concentration was ~3,000 ppm. Concentrations in indoor and outdoor air were measured on a six-minute cycle with the calibrated CO_2 monitors installed in each classroom. The ventilation rate in air changes per hour (h^{-1}) was calculated as the slope of the least squares linear regression of the natural log of indoor minus outdoor CO_2 concentrations versus time.

Air samples were simultaneously collected inside and outdoors over an approximate one-hour period using pump systems set to operate at ~50 cm^3 min^{-1} and ~1 L min^{-1} for VOCs and aldehydes, respectively.

Data Analysis

Emission rates (ERs) of the target compounds in mass per time (mg h^{-1}) were calculated for the chamber study and derived for the classrooms assuming the chamber and the classrooms were ideal continuously-stirred tank reactors (CSTRs) operating at near steady-state conditions (ASTM, 1997a). Net losses of compounds due to factors other than ventilation were ignored. The steady-state form of the mass-balance model for CSTRs was used:

$$ER = Q\,(C - C_0) \tag{1}$$

where Q is the chamber inlet gas flow rate (m^3 h^{-1}) or the flow rate of outside air (m^3 h^{-1}) into the classrooms; C is the air concentration of the compound in the chamber or classroom (µg m^{-3}); and C_0 is the chamber background concentration or the outdoor air concentration (µg m^{-3}).

Area-specific emission rates or emission factors (EFs) in mass per area-time (µg m^{-2} h^{-1}) were calculated as:

$$EF = \frac{Q\ \ (C - C_O)}{A} \tag{2}$$

where A is the material surface area (m^2) for the chamber study and the total floor area for the classroom study.

Laboratory Study Results and Selection of Materials

The alternate floor coverings, tackable wall panels and acoustic ceiling panels for the source-modified classrooms primarily were selected to have lower emissions of both toxic compounds of concern and odorous compounds than the standard materials typically used by the RC manufacturer. Attainment of reductions in the expected classroom concentrations of formaldehyde was a particularly high priority as formaldehyde is a potent sensory irritant and is considered a probable human carcinogen. Other selection criteria for the alternate materials included performance parameters (*e.g.*, durability, maintenance requirements, and sound reduction properties), appearance, cost, and acceptance by the SD and the RC manufacturer. The project task paid the incremental material and labor costs associated with upgrading to the alternate materials. Additionally, the new student desks in each RC were specified to have fully encapsulated tops to eliminate these furnishings as a strong VOC source.

SD A routinely installed an upgraded carpet in their schools and specified this carpet for use in both study classrooms. It was a Nylon-6,6 fiber broadloom carpet bonded to the plywood subfloor with a solvent-free full-spread adhesive. Approximately 12 gallons (45 L) of adhesive were used per classroom. A Nylon-6,6 fiber carpet with an olefin, chlorine-free hardback was selected for use in the SD B modified classroom (SDB-A). This was intended to be installed using a dry adhesive mesh system. The mesh, however, did not bond properly to the plywood, and the carpet was installed with a solvent-free full-spread adhesive. In standard classroom SDB-B, an intermediate grade, Nylon-6 fiber broadloom carpet was installed, also with a solvent-free full-spread adhesive.

The same commercial grade, sheet vinyl floor covering was used in each RC. However, the area of sheet vinyl floor covering was larger in the SD A classrooms than in the SD B classrooms.

The RC manufacturer follows standard industry practice and finishes the four walls of their RCs with vinyl-covered fiberboard tackable wall panels. The alternate material selected for the modified RCs was the same fiberboard panel covered with Teflon®-coated vinyl. This coated vinyl material is primarily intended for use on surfaces in need of frequent cleaning, and may serve as a partial barrier to limit VOC diffusion.

The manufacturer finishes the grid ceilings of their RCs using a fiberglass panel with a vinyl coating on its exposed surface. A mineral fiber ceiling panel with no detectable emissions of formaldehyde was selected as the alternate material for the modified RCs.

The only other interior finish material with a significant surface area was the built-in cabinetry. This cabinetry and the associated countertops were high quality units constructed with surfaces of the composite wood components encapsulated with laminate. This surface treatment substantially reduces the emissions of formaldehyde (Kelly *et al*., 1999). As our specifications for cabinetry were met and no lower emitting materials at reasonable cost were available, the cabinetry components were not tested for emissions of VOCs.

The standard and alternate materials selected and used to finish the interiors of the four classrooms are listed in Table 2 along with their exposed surface areas.

Emission factors (EFs) for chemicals of concern and odorous compounds emitted by the eight standard and alternate materials are given in Table 3. The compounds in this and subsequent tables are listed by chemical class (*i.e.*, alcohols and glycol ethers, ketones, aldehydes, esters, terpene hydrocarbons and terpenols, aromatic hydrocarbons, chlorinated hydrocarbons, and nitrogen-containing compounds) and then in order of decreasing vapor pressure or volatility within class. Lower LOQs for the EFs were approximately 3 $\mu g\ m^{-2}\ h^{-1}$ for formaldehyde and acetaldehyde and 1.5 $\mu g\ m^{-2}\ h^{-1}$ for the other compounds. Values below these limits were not reported. In total, there were five odorous compounds (α-terpineol, hexanal, nonanal, decanal, and 4-phenylcyclohexene) and 11 toxic compounds of concern emitted by the eight materials. The specification of the carpet used in classroom SDB-B was changed subsequent to completion of the chamber study. Thus, the EFs for a Nylon-6 fiber carpet originally tested as an alternate were used as proxies for the installed material's EFs.

For each material, the calculated VOC EFs were multiplied by the projected surface area of the material exposed in a classroom to predict the ERs attributable to the material. Then for each compound, the ERs from the various materials in a classroom were summed (Table 4). The predicted formaldehyde ERs were largely attributable to the standard ceiling panel. 1,2,4-Trimethylbenzene, 1-methyl-2-pyrrolidinone, and di(ethylene glycol)butyl ether were almost entirely attributable to the standard wall panel. The alternate wall panel was predicted to virtually eliminate these compounds and measurably reduce the emissions of vinyl acetate. A tradeoff associated with using the alternate wall panel was the emergence of predicted toluene emissions in the modified classrooms. Carpets were the source of the caprolactam emissions in the SD B classrooms, with the Nylon-6 carpet being the predominant source.

Classroom Study Results

Ventilation Rates

The code minimum ventilation rate for school classrooms is 15 cfm (7 L s^{-1} or 26 m^3 h^{-1}) per occupant (ASHRAE, 1999). The numbers of occupants were the obtained classroom enrollments, approximately 30 in SD A and 20 in SD B, plus one teacher. Thus, the design ventilation rates were 465 cfm (790 m^3 h^{-1}) for SD A and 315 cfm (535 m^3 h^{-1}) for SD B.

Ventilation rates measured by CO_2 tracer gas decay and calculated airflow rates in each of the classrooms for the pre-occupancy, fall and spring sampling events are presented in Table 5. As noted, the standard HPAC systems used for the pre-occupancy measurements were not adjusted until later, and the fall and spring measurements were made with the IDEC systems. The calculated airflow rates were lower during the 27-week sampling event when the IDEC systems were predominantly in the heating mode. Other than pre-occupancy, the airflow rates were higher than, or approximately equivalent to, the code-minimum ventilation requirements except at 27 weeks in classrooms SDA-A (39% low) and SDB-B (12% low).

VOC Emission Rates

Decreases in the derived emission rates (ERs) of seven selected VOCs, including formaldehyde and acetaldehyde, with time after installation are illustrated in Figures 1 and 2 for unmodified classrooms SDA-B and SDB-B, respectively. Lower LOQs for indoor minus outdoor (*i.e.*, adjusted indoor) concentrations were used to estimate lower LOQs for the ERs. There was a substantial drop in ERs between the time of installation and eight weeks after first occupancy, when many of the values were below LOQs. ERs of VOCs generally decreased between eight and 27 weeks; however, some of these changes were difficult to evaluate because the values were below their LOQs. In the final period, the formaldehyde and acetaldehyde ERs for classroom SDB-B were low but still quantifiable due to the corresponding low ventilation rate.

The derived ERs of formaldehyde in classroom SDB-A were notable. Initially, this classroom had the lowest formaldehyde ER of 2.4 mg h^{-1}. At eight weeks, the ER increased more than ten-fold to 27 mg h^{-1}. In the subsequent final sampling event, the ER of 2.1 mg h^{-1} was consistent with the formaldehyde values derived for the other classrooms. We were unsuccessful in our attempt to identify the transient source of the elevated fall ER. An inspection of the classroom shortly after the eight-week sampling event revealed the presence of teaching aids. The date of introduction was determined to be prior to the event. The teaching aids were personal pegboards constructed of hardboard with one exposed surface and personal dry-erase marking boards constructed of particleboard with one exposed surface. Both hardboard and particleboard have been identified as sources of formaldehyde (Kelly *et al*., 1999; Hodgson *et al*., 2002). Emissions of formaldehyde from specimens of these products collected from the classroom were measured in small-scale chambers at 96 h without conditioning. The measured EFs for pegboards and marking boards were 86 and 570 µg m^{-2} h^{-1}, respectively. Based on the sizes and numbers of teaching aids in the classroom, we predicted they could contribute 0.66 mg h^{-1} to the total derived formaldehyde ER, or only about 2.5 % of the total. Thus, these materials were unlikely to be the source of the elevated formaldehyde ER.

Classroom VOC Concentrations

VOC concentrations measured in the classrooms when they were operating with the IDEC systems during the fall semester provided the best available measures of concentrations when the classrooms were new and operating with near code-minimum ventilation rates. We must note, however, the teachers did not continuously operate the IDEC systems during some of the individual classroom/week sampling events, especially in the fall 2001 cooling season. Thus, the average ventilation rates during some of the measurement periods may have been below the minimum code requirements used to predict concentrations. The average adjusted (outdoor concentration subtracted) indoor concentrations and concentration ranges of 15 VOCs, which were quantified in the chamber study, are presented by classroom in Table 6. One of the compounds from the chamber study, di(ethylene glycol)butyl ether, was not detected in any of the classroom samples. Among the four classrooms, week-to-week variability as shown by the concentration ranges was generally lowest for classroom SDA-A. This was presumably the result of relatively consistent operation of the IDEC system in this RC. Only formaldehyde had average adjusted indoor concentrations above 5 parts-per-billion (ppb). Among the other compounds, only phenol, acetaldehyde, hexanal, nonanal, and caprolactam had average concentrations above 1 ppb.

Discussion

Comparisons of adjusted indoor VOC concentrations and derived classroom ERs with their corresponding predicted values are indicators of how well VOC sources in classrooms can be estimated based on data generated by the small-scale laboratory studies. Due to the uncertainties involved in this process, we defined the boundary for acceptable agreement as up to a factor of two divergence between actual and predicted values. The derived classroom ERs, which were determined immediately prior to occupancy and eight weeks after first occupancy for the 15 VOCs quantified in the chamber study, were compared to the predicted ERs of these VOCs. Comparisons for seven of these compounds in standard classrooms SDA-B and SDB-B are depicted in Figures 1 and 2. Compounds for which the derived ERs in either the pre-occupancy or the eight-week sampling event agreed within a factor of two of the predicted rates in two or more classrooms were phenol, formaldehyde, acetaldehyde, hexanal, toluene, and caprolactam. The primary sources of these compounds appear in Table 3. The un-coated, vinyl-covered tackable wall panel used in the standard classrooms was predicted to be a relatively large source of vinyl acetate, 1,2,4-trimethylbenzene and 1-methyl-2-pyrrolidinone. The Teflon®-coated, vinyl-covered wall panel used in the modified classrooms also was predicted to be a large source of vinyl acetate. The comparisons of derived and predicted ERs showed the wall panels installed in the classrooms to be substantially lower sources of these compounds than forecasted by the chamber study. Possible reasons are rapid decay in the emissions of these compounds from the panels and/or real differences between the tested and installed materials.

The adjusted indoor concentrations of 15 VOCs measured when the classrooms were operating with the IDEC systems near code-minimum ventilation rates during the fall semester were averaged and were compared in Table 7 to concentrations predicted by dividing the summed VOC ERs by their corresponding design ventilation rates. For more than one-third of the individual comparisons for which there were measurable classroom concentrations, 16 of 42 possible comparisons, the average measured concentrations were within a factor of two of the predicted concentrations.

The same classroom VOC concentrations comprised the most useful data to evaluate the effectiveness of material selection for reducing potential classroom exposures. Thus, adjusted indoor concentrations measured in modified and standard classrooms on weeks two, four, six and eight at each school district were paired by week creating eight pairs of measurements for the combined school districts. The hypothesis, which stated there was no significant difference in mean concentrations between modified and standard RCs when both were operating with the IDEC systems, was tested with a paired Student's t test (two-tailed test, seven degrees of freedom, P = 0.05). Ten VOCs (phenol, formaldehyde, acetaldehyde, hexanal, nonanal, toluene, 1,2,4-trimethylbenzene, naphthalene, 1-methyl-2-pyrrolidinone and caprolactam) had sufficient numbers of data points above LOQs for the analysis. For caprolactam, the test was run with only the four pairs of measurements from SD B since there was no measured source of caprolactam in either RC at SD A. Statistically significant differences in mean adjusted indoor VOC concentrations between modified and standard RCs were observed for phenol, hexanal, nonanal, 1-methyl-2-pyrrolidinone, and caprolactam. In each case, the concentrations were lowest in the modified classrooms. The mean concentration differences between modified and standard classrooms were less than 1 ppb with the exception of caprolactam with a 4.2-ppb difference.

Two studies have measured VOC concentrations and ventilation rates in new, HUD-code manufactured houses using methodologies similar to those of the present study (Hodgson *et al.*, 2000, 2002). The ranges of derived VOC EFs in the four RCs eight weeks after first occupancy were compared to the house values in Table 8. These comparisons were made for 14 compounds quantified in the RCs and in one or both house studies. The classroom EFs of 2-butanone, hexanal, heptanal, octanal, 2-octenal, α-pinene, and d-limonene were below the values derived for the houses, while formaldehyde EFs, excluding the uncharacteristically high value in classroom SDB-A, were somewhat lower in the RCs. Toluene EFs were higher in the RCs. The lower classroom EFs of higher molecular weight aldehydes and terpene hydrocarbons were consistent with the low quantities of unfinished composite wood surfaces in the cabinetry, a major source of these compounds in the houses. In addition, the installation of the classroom carpets directly over the plywood subfloor with full-spread adhesive may have contributed to the low emissions of formaldehyde and other VOCs associated with plywood in the house studies.

Conclusions

Both the standard and alternate materials used to construct the interiors of these RCs generally were shown to be low sources of toxic and odorous VOCs. As the result of low material emissions and the substantially higher ventilation rates required in classrooms than in other settings, e.g., houses, due to higher occupant densities, indoor concentrations of most VOCs were relatively low. In fact, when the classrooms were operating during the fall 2001 cooling season with the advanced IDEC systems, only the average adjusted indoor concentrations of formaldehyde exceeded 5 ppb, while the majority of the target compounds had average concentrations below 1 ppb.

Emission rates (ERs) of most VOCs derived from interior materials were shown to decrease substantially with time following installation of the RCs. As a consequence of these decreases, the derived ERs of many compounds were below lower limits of quantitation at eight and 27 weeks after first occupancy.

In roughly one third of the compared cases, VOC ERs and concentrations in the RCs were predicted with reasonable accuracy, *i.e.*, within a factor of two, based on the results of the laboratory study of material emissions. Some of the largest discrepancies occurred because the standard and alternate vinyl-covered wall panels installed in the RCs were lower sources of VOCs than projected from the laboratory study. An exception was formaldehyde in one RC; although the source was not identified, the transient elevation in the classroom likely was not due to the interior finish materials.

Differences in mean VOC concentrations over the fall 2001 cooling season between modified and standard RCs were small, *i.e.*, typically less than 1 ppb on average, when the classrooms were operated with the IDEC systems. Nevertheless, for five compounds, these differences were statistically significant. Lower concentrations of phenol in modified RCs likely were due to the use of Teflon®-coated vinyl-covered wall panels and/or the mineral fiber ceiling panels. Lower concentrations of 1-methyl-2-pyrrolidone likely were due to the alternate wall panels. The use of carpets without Nylon-6 fibers resulted in low to non-detectable concentrations of caprolactam.

The emissions of VOCs from the standard materials used by this manufacturer were sufficiently low to achieve generally acceptable air quality in the RCs, assuming code-minimum ventilation rates were maintained. Under these conditions, the small magnitude of the beneficial effects attributable to the use of alternate interior finish materials suggested it might not be imperative to use such materials.

In general, it is essential to ensure the broad range of materials potentially used to construct the interiors of new classrooms do not seriously impact indoor air quality, even when ventilation rates fall below code requirements due to teacher preference (*e.g.*, as observed in this study), improper adjustment, or malfunction. Laboratory-based material testing combined with modeling and field validation to select low VOC-impact interior finish materials was demonstrated to be sufficiently accurate to inform the material selection process with the goal of reducing potential occupant exposures to toxic and objectionable indoor air pollutants.

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Table 1. Toxic chemicals of concern in California

California Regulatory Lists of Toxic Chemicals	www.URL
Air Toxics Hot Spots Program Risk Assessment Guidelines; Chemicals with Established Noncancer Chronic Reference Exposure Levels (RELs)[a]	oehha.org/air/chronic_rels/
Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65); Chemicals Known to the State to Cause Cancer or Reproductive Toxicity[b]	oehha.org/prop65/prop65_list/newlist.html
Substances Identified as Toxic Air Contaminants (TACs) by the Air Resources Board[c] (includes all U.S. EPA Hazardous Air Pollutants)	arb.ca.gov/toxics/taclist.htm

a. Cal/EPA, 2003a.
b. Cal/EPA, 2003b.
c. Cal/EPA, 1999.

Table 2. Projected surface areas of standard and alternate interior finish materials installed in four classrooms

Material Description	Lab. Code	Surface Area (m^2) Sch. Dist. A Classrm. SDA-A	SDA-B	Sch. Dist. B Classrm. SDB-A	SDB-B
FLOOR					
Nylon-6,6 broadloom carpet[a,b]	BLC2	72.0	72.0		
Nylon-6 broadloom carpet[a]	BLC3[c]				81.5
Nylon-6,6 olefin hardback carpet[a,b]	HBC			81.5	
Sheet vinyl flooring	SVF	12.8	12.8	3.3	3.3
WALLS					
Vinyl-covered fiberboard wall panels	VWP1		92.0		92.0
Teflon®-coated vinyl-covered fiberboard wall panels[b]	VWP2	92.0		92.0	
CEILING					
Fiberglass ceiling panels	FCP		84.8		84.8
Mineral fiber ceiling panels[b]	MCP2	84.8		84.8	

a. Bonded to plywood subfloor with solvent-free, full-spread adhesive.
b. Alternate interior finish material for source-modified classrooms.
c. Installed carpet had similar face fibers as carpet designated BLC3 in laboratory study.

Table 3. Laboratory measured VOC emission factors for standard and alternate interior finish materials installed in four classrooms

	Emission Factor ($\mu g\ m^{-2}\ h^{-1}$)							
	Floor Coverings				Wall Panels		Ceiling Panels	
Compound	BLC2[a]	BLC3[b]	HBC	SVF	VWP1	VWP2	FCP	MCP2
Phenol				240	53	6.1	18.1	
DEGBE[c]	6.0				50			
2-Butanone	3.4							
Formaldehyde			4.0				32	
Acetaldehyde	24	13.0		12.8	46	23		
Hexanal	41	46						
Nonanal		6.6						2.6
Decanal	1.7	2.7			7.5	2.0		
Vinyl acetate					840	290		
α-Terpineol	2.6							
Toluene						20		
1,2,4-TMB[c]				26	100			
Naphthalene	3.4							
4-PCH[c]		2.6						
NMP[c]					158			
Caprolactam		126	8.5					

a. Material identification codes used in laboratory study are defined in Table 2.
b. EFs for Nylon-6 carpet originally tested as alternate were used as proxies for installed material's EFs.
c. DEGBE = Di(ethylene glycol)butyl ether; 1,2,4-TMB = 1,2,4-trimethylbenzene; 4-PCH = 4-phenylcyclohexene; NMP = 1-methyl-2-pyrrolidinone.

Table 4. Predicted emission rates of toxic and odorous VOCs in four classrooms

	Predicted Emission Rate (mg h^{-1})			
	Sch. Dist. A Classroom		Sch. Dist. B Classroom	
Compound	SDA-A	SDA-B	SDB-A	SDB-B
Phenol	3.6	9.5	1.35	7.2
DEGBE*	0.43	5.0	--	4.6
2-Butanone	0.24	0.24	--	--
Formaldehyde	--	2.7	0.33	2.7
Acetaldehyde	2.3	4.4	2.1	5.4
Hexanal	3.0	3.0	--	3.8
Nonanal	0.22	--	0.22	0.54
Decanal	0.31	0.81	0.18	0.91
Vinyl acetate	27	77	27	77
α-Terpineol	0.19	0.19	--	--
Toluene	1.87	--	1.87	--
1,2,4-TMB*	0.34	9.5	0.09	9.3
Naphthalene	0.24	0.24	--	--
4-PCH*	--	--	--	0.21
NMP*	--	14.5	--	14.5
Caprolactam	--	--	0.69	10.3

*Compound abbreviations defined in Table 3.

Table 5. Ventilation rates measured by CO_2 tracer gas decay and calculated outdoor air (OA) flow rates in four classrooms for the pre-occupancy, fall (eight-week) and spring (27-week) sampling events

Ventilation Parameter	Sch. Dist. A Classroom SDA-A	SDA-B	Sch. Dist. B Classroom SDB-A	SDB-B
PRE-OCCUPANCY[a]				
Ventilation rate (h^{-1})	8.2	4.5	1.49	1.74
OA Flow rate (m^3 h^{-1})	1,800	990	330[b]	380[b]
FALL SEMESTER[c]				
Ventilation rate (h^{-1})	3.5	4.2	3.4	2.8
OA Flow rate (m^3 h^{-1})	780	920	740	610
SPRING SEMESTER[c]				
Ventilation rate (h^{-1})	2.2	3.5	2.4	2.1
OA Flow rate (m^3 h^{-1})	480[b]	760	530	470[b]

a. Standard HPAC system prior to final adjustment of airflow rates. SD A RCs had option allowing up to 50%, instead of 25%, OA intake.
b. More than 10% below design ventilation rate.
c. IDEC system.

Table 6. Indoor minus outdoor concentrations of toxic and odorous VOCs (average and range) in four classrooms during fall cooling season with IDEC system operating

	Concentration (ppb)							
	School Dist. A Classroom				School Dist. B Classroom			
	SDA-A (n = 4)		SDA-B (n = 4)		SDB-A (n = 4)		SDB-B (n = 5)	
Compound	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
Phenol	0.56	0.34-0.75	1.62	0.80-2.5	0.41	<0.08-0.98	0.84	0.21-1.37
2-Butanone	<0.26	<0.26-0.28	<0.26	<0.26-0.36	<0.26	<0.26-0.36	<0.26	<0.26-0.39
Formaldehyde	4.2	3.0-4.7	9.9	3.5-19.2	12.2	8.4-17.4	6.1	2.8-10.6
Acetaldehyde	0.64	<0.42-1.30	1.79	<0.42-4.8	2.2	<0.42-5.2	1.50	<0.42-3.0
Hexanal	<0.84	<0.84-0.90	1.62	<0.84-3.0	1.96	1.33-3.0	2.8	1.23-3.6
Nonanal	0.92	0.62-1.22	1.41	0.66-2.1	1.06	0.34-1.68	2.3	0.98-3.7
Decanal	<0.36	<0.36-0.54	0.36	<0.36-0.54	<0.36	<0.36	0.40	<0.36-0.95
Vinyl acetate	<0.06	<0.06	0.11	<0.06-0.20	0.22	0.10-0.43	<0.06	<0.06
α-Terpineol	<0.01	<0.01	0.02	<0.01-0.05	0.04	0.03-0.06	0.06	<0.01-0.12
Toluene	0.41	0.26-0.70	0.42	0.25-0.62	1.06	0.46-1.86	0.52	0.27-0.98
1,2,4-TMB*	0.08	0.06-0.10	0.19	0.08-0.30	0.16	0.07-0.26	0.09	0.03-0.15
Naphthalene	0.04	0.04-0.05	0.20	0.09-0.30	0.07	0.04-0.14	0.01	<0.01-0.04
4-PCH*	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.09	<0.02-0.15
NMP*	<0.02	<0.02	0.34	0.16-0.53	0.06	<0.2-0.12	0.91	0.22-1.79
Caprolactam	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22-0.30	4.8	2.3-6.5

*Compound abbreviations defined in Table 3.

Table 7. Comparison of predicted and average measured indoor minus outdoor VOC concentrations for School Districts A and B source-modified and standard classrooms operating with IDEC systems in fall cooling season. Predicted values in bold text are within factor of two of measurements

	Concentration (ppb)							
	School District A Classroom[a]				School District B Classroom[b]			
	SDA-A		SDA-B		SDB-A		SDB-B	
Compound	Predicted	Average Measured	Predicted	Average Measured	Predicted	Average Measured	Predicted	Average Measured
Phenol	1.19	0.56	**3.1**	1.62	**0.66**	0.41	3.5	0.84
2-Butanone	0.11	<0.26	0.11	<0.26	--	<0.26	--	<0.26
Formaldehyde	--	4.2	2.8	9.9	0.50	12.2	**5.1**	6.1
Acetaldehyde	1.59	0.64	**3.1**	1.79	**2.2**	2.2	5.6	1.50
Hexanal	**0.91**	**<**0.84	**0.91**	1.62	--	1.96	**1.73**	2.8
Nonanal	0.05	0.92	--	1.41	0.07	1.06	0.17	2.3
Decanal	0.06	<0.36	0.16	0.36	0.05	<0.36	**0.27**	0.40
Vinyl acetate	9.7	<0.06	28	0.11	14.3	0.22	41	<0.06
α-Terpineol	0.04	<0.01	**0.04**	0.02	--	0.04	--	0.06
Toluene	**0.63**	0.41	--	0.42	**0.93**	1.06	--	0.52
1,2,4-TMB[c]	**0.09**	0.08	2.5	0.19	0.03	0.16	3.5	0.09
Naphthalene	**0.06**	0.04	0.06	0.20	--	0.07	--	0.01
4-PCH[c]	--	<0.02	--	<0.02	--	<0.02	**0.06**	0.09
NMP[c]	--	<0.02	4.5	0.34	--	0.06	6.7	0.91
Caprolactam	--	<0.22	--	<0.22	0.28	<0.22	**4.2**	4.8

a. Design ventilation rate 790 $m^3 h^{-1}$.
b. Design ventilation rate 535 $m^3 h^{-1}$.
c. Compound abbreviations defined in Table 3.

Table 8. Range of derived VOC emission factors in four classrooms eight weeks after first occupancy compared to derived emission factors from two studies of new, unoccupied manufactured houses

Compound	Derived Emission Factor ($\mu g\ m^{-2}\ h^{-1}$) 4 Classrooms Range	4 Manuf. Houses[a] GM[b] (Range)	1 Manu. House Value[c]
Phenol	<2.4-3.6	9.6 (2.2-16.6)	--
2-Butanone	<5.4-7.9	22 (8.6-90)	--
Formaldehyde	<23-42[d]	45 (29-68)	62±10
Acetaldehyde	<10.9-16.6	17 (6-46)	26±4.4
Pentanal	<7.0	--	50±8.1
Hexanal	<37	77 (46-137)	181±31
Heptanal	<3.5	7.7 (3.9-12.9)	16.9±2.5
Octanal	<8.8	14.1 (7.4-22)	29±4.4
2-Octenal	<3.4	--	13.1±1.9
Nonanal	<25	14.7 (3.3-23)	28±4.4
α-Pinene	4.1-14.9	105 (41-189)	156±25
d-Limonene	4.5-9.6	18.5 (9.9-36)	28±4.4
Toluene	11.2-34	3.9 (<2.7-9.6)	--
Styrene	1.08-2.2	4.1 (1.8-15.5)	--

a. From Table 5, Hodgson *et al*. (2000).
b. Geometric mean (GM) and range for measurements made in four houses on three occasions over nine months after installation.
c. Calculated from Table 5, Hodgson *et al*. (2002); derived EFs from house measurements ± one standard deviation.
d. Excludes 320-$\mu g\ m^{-2}\ h^{-1}$ value measured in classroom SDB-A (see text).

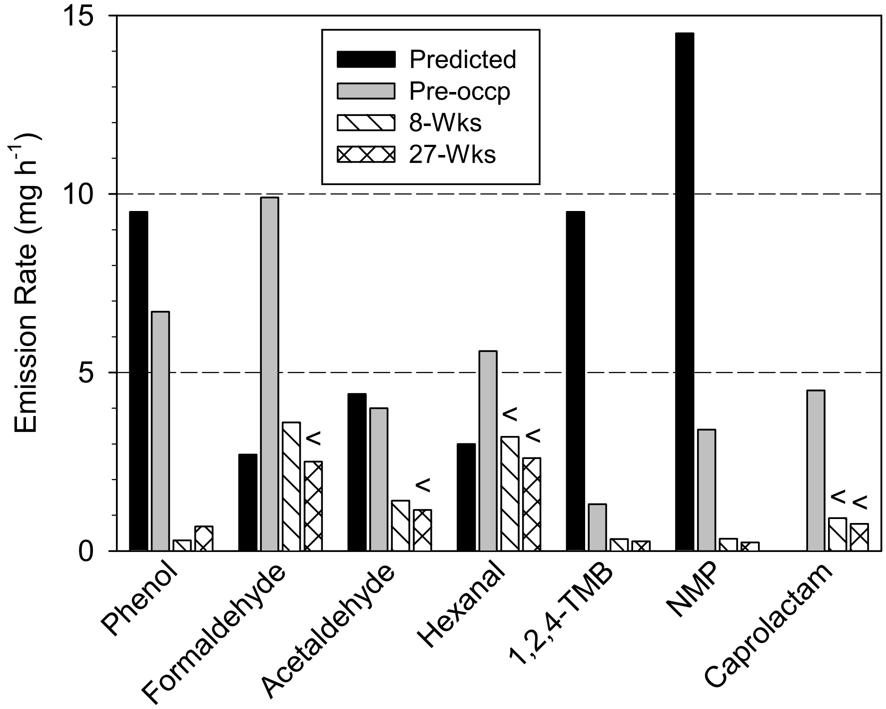

Figure 1. Predicted emission rates of selected VOCs in classroom SDA-B compared to derived emission rates measured prior to occupancy and at eight and 27 weeks after first occupancy. The "<" symbols indicate values at or below the empirical lower limit of quantitation for the analysis.

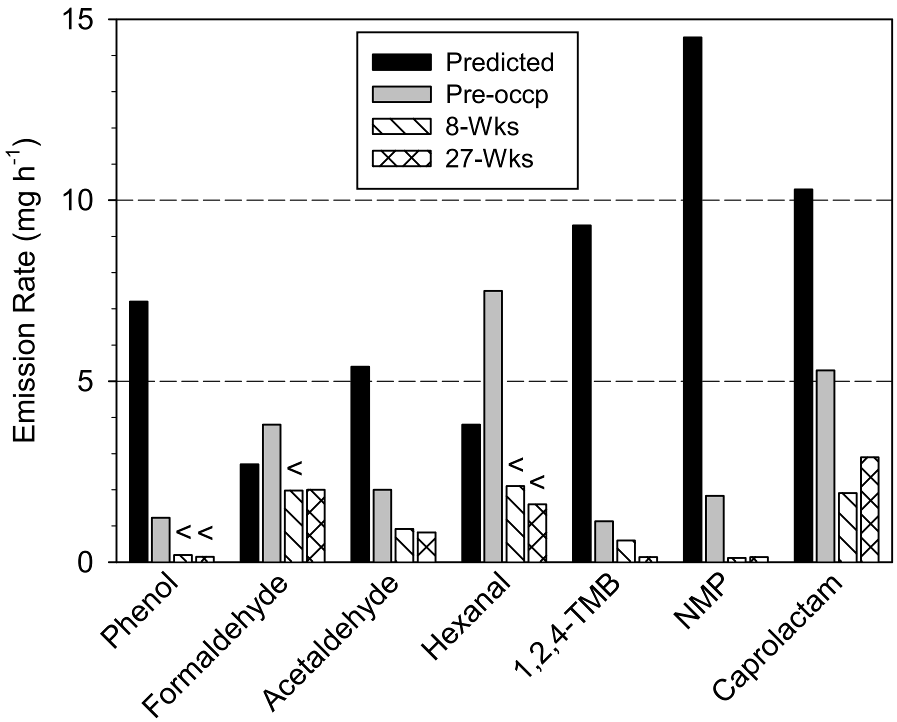

Figure 2. Predicted emission rates of selected VOCs in classroom SDB-B compared to derived emission rates measured prior to occupancy and at eight and 27 weeks after first occupancy. The "<" symbols indicate values at or below the empirical lower limit of quantitation for the analysis.